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Development of a Drilling-Free Staged Cementing Tool with Acid Resistance and Gas-Tight Integrity

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Abstract

To address the issues of poor corrosion resistance and inadequate gas sealing in staged cementing tools for deep wells, ultra-deep wells, and CCUS injection-production wells under acidic media (e.g., CO_2), an Acid-Resistant Media Corrosion Gas Sealing Drilling-Free Staged Cementing Tool has been developed. By optimizing the tool's gas-sealing structure and selecting high-performance sealing ring materials, metal materials with corrosion-resistant alloys grade 13Cr or higher (recommended by ECE corrosion simulation software) were used for tool fabrication. Laboratory performance tests verified:110 MPa hydraulic sealing capacity, 36.5 MPa gas sealing capacity, Reliable drilling-free performance under 35° well inclination.Field testing in a Changqing Oilfield well achieved successful staged cementing with a 100% cementing qualification rate. This tool resolves corrosion failure risks in acidic environments and enhances wellbore sealing integrity.

Keywords

Staged Cementing; Drilling-Free; Corrosion Resistance; Gas Sealing.

1. Introduction

As the development scale of deep wells, ultra-deep wells, and CCUS (Carbon Capture, Utilization, and Storage) injection-production wells continues to expand, their deeply buried target formations necessitate exceptionally large cement slurry volumes when employing single-stage cementing. This results in prolonged operational times and often leads to insufficient casing return depth, consequently compromising cementing quality [1-3]. To address these issues of low efficiency and poor quality [4], multi-stage cementing has become the primary approach in oilfield operations, with the stage cementing collar serving as the key enabling tool. Moreover, since these wells frequently contain acidic corrosive media such as CO2, severe corrosion is commonly observed in downhole tubulars [5-6], including cemented casings and tools.

In summary, multi-stage cementing significantly enhances wellbore integrity. However, existing drillable stage cementing collars lack the requisite corrosion resistance against acidic media and reliable gas-tight seal integrity. Addressing these critical technical limitations necessitates the urgent development of acid-corrosion-resistant, gas-tight seal, drillable stage cementing collars. This innovation would bridge a significant domestic technology gap and supplant conventional drillable stage cementing tools. The resulting advancement promises to elevate tool safety and reliability, reduce operational expenditures, and improve cementing quality alongside wellbore seal integrity within challenging acidic environments.

2. Structure and Operating Principle of the Tool

2.1. Overall Structure and Key Performance Parameters of the Drilling-Free Staged Cementing Tool

The corrosion-resistant, gas-tight sealed drilling-free staged cementing tool comprises a housing, a closed sliding sleeve (initially shut position), a closing plug seat, an open sliding sleeve, an opening plug seat, a bottom sub, a hollow plug, a flexible plug, an opening plug, and a closing plug. The tool structure is illustrated in Figure 1. Within the housing, the closing plug seat, closed sliding sleeve, opening plug seat, open sliding sleeve, and the main flexible plug are sequentially arranged. The bottom sub is connected to the lower end of the housing via threaded connections. Both the closed sliding sleeve and the open sliding sleeve are secured to the housing by shear pins. Cementing ports are machined through the housing wall.

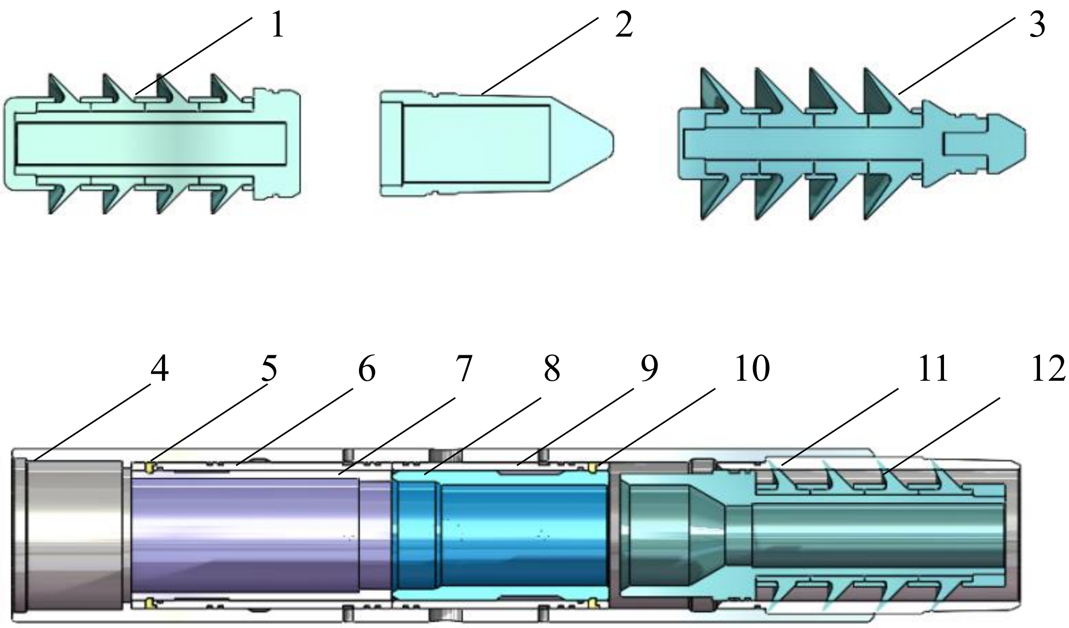

Figure 1 Schematic diagram of tool structure
1—Closing plug；2—Opening plug；3—Flexible plug；4—Housing；5—Upper lock block；6—Closed sliding sleeve；7—losing plug seat；8—Opening plug seat；9—Open sliding sleeve；10—Lower lock block；11—Bottom sub；12—Hollow plug

During tool assembly, the process begins with constructing sub-assemblies: Sub-Assembly 1 integrates the closed sliding sleeve, closing plug seat, and upper lock block; Sub-Assembly 2 combines the open sliding sleeve, opening plug seat, and lower lock block; and Sub-Assembly 3 joins the bottom sub with the hollow plug. Final integration proceeds by inserting Sub-Assembly 1 and Sub-Assembly 2 into the housing and securing them with shear pins, followed by connecting Sub-Assembly 3 to the housing via threaded coupling—with special care taken to install an anti-rotation screw at the threaded interface. The complete technical specifications of the tool are detailed in Table 1.

Table 1 Tool technical parameters

Tool length/ mm	Noumenon Maximum outer Diameter/ mm	Noumenon Maximum inner Diameter /mm	Flexible plug length/ mm	Opening plug length/ mm	Closing plug length/ mm	liquid Sealing ability /MP	gas Sealing ability /MPa	Open pressure of circulating hole /MPa	Closing pressure of circulating hole /MPa

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950	160	141	320	215	273	105	35	6-8	5-6

2.2. Gas-Tight Seal Optimization Design for the Tool

The staged cementing tool adopts a multi-stage elastomeric seal structure to enhance its gas-tight sealing capability. Critical factors governing the tool's gas-sealing performance include seal interference fit, groove geometry design, material selection, and surface roughness of tool components.

(1) Seal Interference Fit: Effective sealing relies on the initial contact stress generated post-installation [7]. During design, the interference must be sufficiently large to ensure the recommended compression ratio is achieved. This contact stress must exceed the operating pressure of the sealed medium and establish adequate seal contact widthto resist medium penetration. Note that larger interference is not universally better. Excessive compression may accelerate material stress relaxation, increase friction to levels impeding movement, or induce extrusion failure.

(2) Groove Geometry Design: Groove width should be slightly wider than the cross-sectional diameter of the installed seal. This provides necessary clearance to accommodate radial expansion caused by fluid absorption, thermal growth, or swelling due to pressure-driven permeation. Width must permit seal radial expansion, while depth reserves space for deformation under compression to prevent excessive shear strain.

(3) Material Selection: Materials with low gas permeability and resistance to acidic media corrosion are essential. Hydrogenated Nitrile Butadiene Rubber (HNBR) is selected for this tool based on its suitability for downhole conditions [8-9].

(4) Surface Roughness: Sealing effectiveness critically depends on microscopic contact between the seal and mating metal surface. The surface roughness (Ra) of the metal component is a key determinant of leakage. Machining precision must ensure Ra < 0.8 μm to minimize gas micro-leakage through surface asperities.

2.3. Working Mechanism of the Drilling-Free Staged Cementing Tool

In staged cementing operations, the dual-stage cementing process is most prevalent. Based on whether the stage cementing tool opens continuously during cement placement, it can be categorized into: Non-Continuous Opening Dual-Stage Cementing and Continuous Opening Dual-Stage Cementing [10]. The operating workflow of the drilling-free staged cementing tool comprises the following steps:

(1) After completing casing running operations, circulate drilling fluid and pump spacer fluid. Conduct primary cementing. Upon finishing primary cementing, drop the flexible plug from the cementing head, pump specialized displacement fluid, circulate drilling fluid, and bump pressure.

(2) Shut down pumps and bleed off wellhead pressure. Drop the gravity-actuated opening plug, and pre-load the closing plug into the cementing head.

(3) After confirming the gravity-actuated opening plug has landed on the opening plug seat (based on calculated drop time), increase pressure using the cementing pump. The opening

plug drives the opening plug seat downward, shearing shear pins and opening the stage cementing tool's ports. Circulate drilling fluid.

(4) Pre-load the closing plug into the cementing head. Pump spacer fluid and conduct secondary cementing.

(5) After completing secondary cementing, pump specialized displacement fluid to drive the closing plug. Monitor the cementing head pressure gauge to confirm the closing plug has landed on the closing plug seat. Increase pressure to drive the closing plug seat and closed sliding sleeve downward, shearing shear pins. The closed sliding sleeve moves down to shut the stage cementing tool's ports.

(6) Perform a final pressure cycle. Pressure forces the dislodgement of the closing plug, closing plug seat, opening plug, opening plug seat, and flexible plug. This enables drill-free operations post-staged cementing.

The workflow of the drilling-free staged cementing process is illustrated in Figure 2.

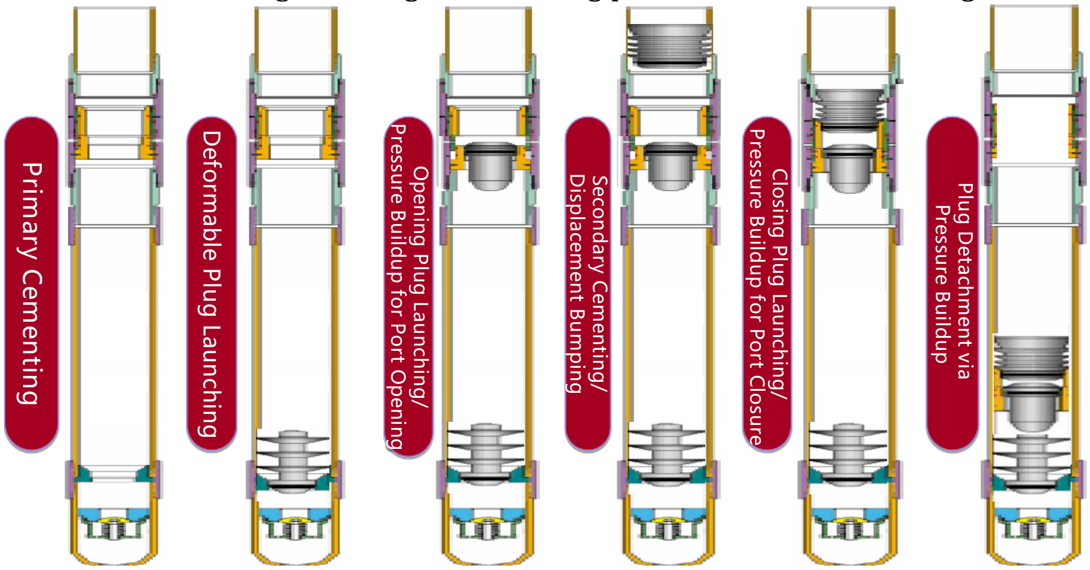

Figure 2 Operational Sequence of the Drilling-Free Staged Cementing Process

3. Material Selection and Processing for Corrosion Resistance in the Drilling-Free Staged Cementing Tool

To address the corrosion of staged cementing tools by downhole acidic media, metallurgical selection for tool manufacturing is paramount. Particularly for CO_2-induced corrosion, wet CO_2 triggers electrochemical attack on carbon steel [11]. CO_2 corrosion—categorized as hydrogen depolarization corrosion—is more severe than strong acid corrosion at equivalent pH levels [12]. Per the NACE RP-0775-2005 standard, corrosion severity is classified by average corrosion rate into four grades: Mild, Moderate, Severe, and Extreme, as detailed in the accompanying table. To ensure long-term, reliable, and safe service in corrosive environments—preventing material-failure-induced accidents and economic losses—materials exhibiting≤0.025 mm/yr average corrosion rates (Mild grade) must be selected.

Table 2 NACE RP-0775-2005 standard

Classification	Average Corrosion Rate(mm/a)
Mild Corrosion	＜0.025
Moderate Corrosion	0.025~0.125
Severe Corrosion	0.125~0.254
Extreme Corrosion	＞0.254

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Current material selection for CO_2-corrosion-resistant metals in staged cementing tools primarily references GB/T 40543-2021 (Petroleum and natural gas industries—Materials selection for casing, tubing, and downhole equipment in high-CO_2 environments). This standard mandates the use of corrosion-resistant alloys (CRA) for downhole tool manufacturing in wet CO_2 gas environments.

After preliminary material screening according to relevant standards, corrosion simulation software is employed for the initial selection of CO_2-resistant materials for the tool. Utilizing ECE (Electronic Corrosion Engineer) software, CRA (Corrosion-Resistant Alloy) materials were evaluated. Field operating conditions were simulated as input parameters, with the corrosion simulation parameters detailed in Table 3. Considering exclusively CO_2 corrosion, the ECE software recommended the following alloys: 13Cr, Super 13Cr, duplex stainless steels (22Cr, 25Cr), and nickel-based alloys (625, 825). All recommended materials exhibited average corrosion rates below 0.025 mm/year, qualifying them as suitable metallic materials for manufacturing drilling-free staged cementing tools.

Table 3 ECE software simulates corrosion conditions

Wellbore Temperature/°C	Wellbore Pressure /MPa	CO2/ Partial Pressure MPa	Cl-/(mg/L)	pH
90	35	5	60660	4.35

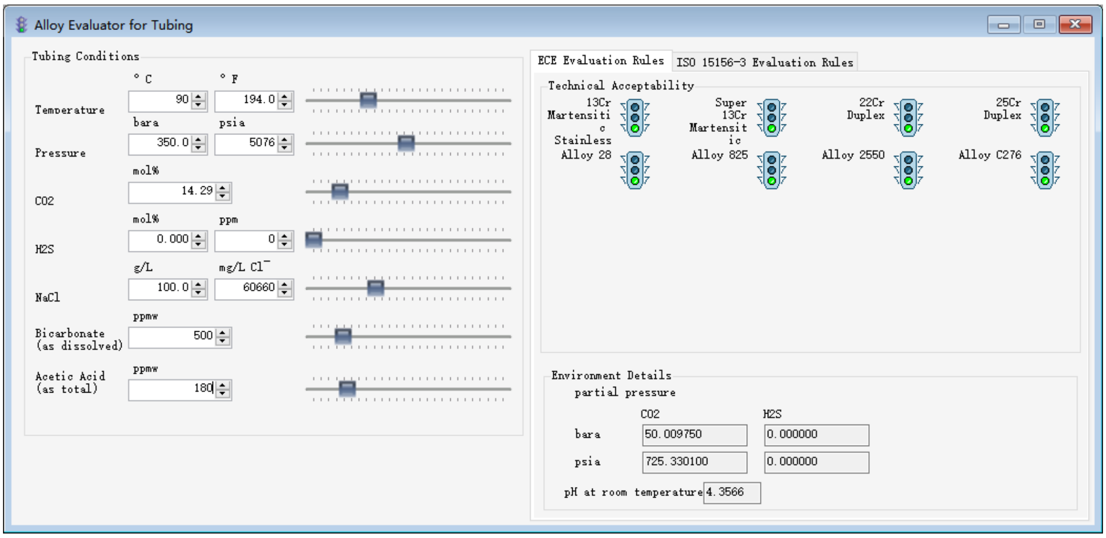

Figure 3 Recommended material selection for ECE software simulation working conditions

4. A Comprehensive Laboratory Performance Evaluation of the Tool

Following the tool's fabrication and assembly, comprehensive surface performance testing is conducted to validate its liquid sealing capability, gas sealing integrity, circulation port actuation function, and non-drillable performance in deviated wells, referencing the specifications of SY/T 5150-2013 Staged Cementing Tool.

4.1. Hydraulic Seal Performance Test

The hydraulic seal integrity test of the staged cementing tool is performed by connecting the tool body to a pressure test head at one end while sealing the opposite end, with all circulation ports closed. Test fluid (typically water) is pressurized via a liquid pressure intensifier pump to the target pressure (e.g., 35 MPa) and held for 5 minutes to validate sealing performance, in compliance with SY/T 5150-2000 section 5.2.5.

Test fluid injection initiates the procedure. During the 4-minute loading phase, pressure ramps up to 110 MPa. Subsequently, a 30-minute pressure-holding phase maintains 110 MPa without replenishment, exhibiting a 0.2 MPa pressure drop. The pressure then linearly reduces to 0 MPa in the one-minute unloading phase. Post-stabilization, the target pressure of 110 MPa is sustained for 20 minutes.

The pressure curve remains steady with virtually no pressure drop, as shown in Figure 6, demonstrating good liquid sealing performance of the tool.

Figure 4 Tool hydraulic Seal Performance Test

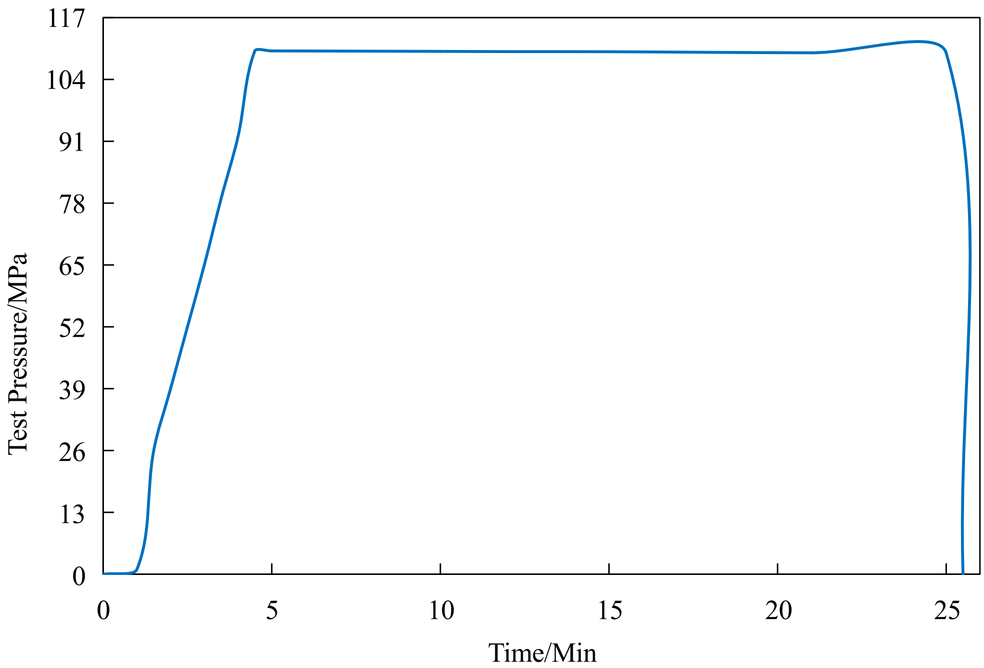

Figure 5 Hydraulic Seal Integrity Test Pressure-Time Profile

4.2. Pneumatic Seal Integrity Test

The staged cementing tool body was connected to a pneumatic adapter at one end. Nitrogen was pressurized into the system via a gas booster pump. The target test pressure of 36.5 MPa was achieved and held for 10 minutes, followed by a stabilized pressure-holding phase of 30 minutes with a recorded pressure drop of 0.2 MPa. The pressurization procedure during the pneumatic seal integrity test is illustrated in Figure 7 (Pressure-Time Profile).

Figure 6 Pneumatic Seal Integrity Test

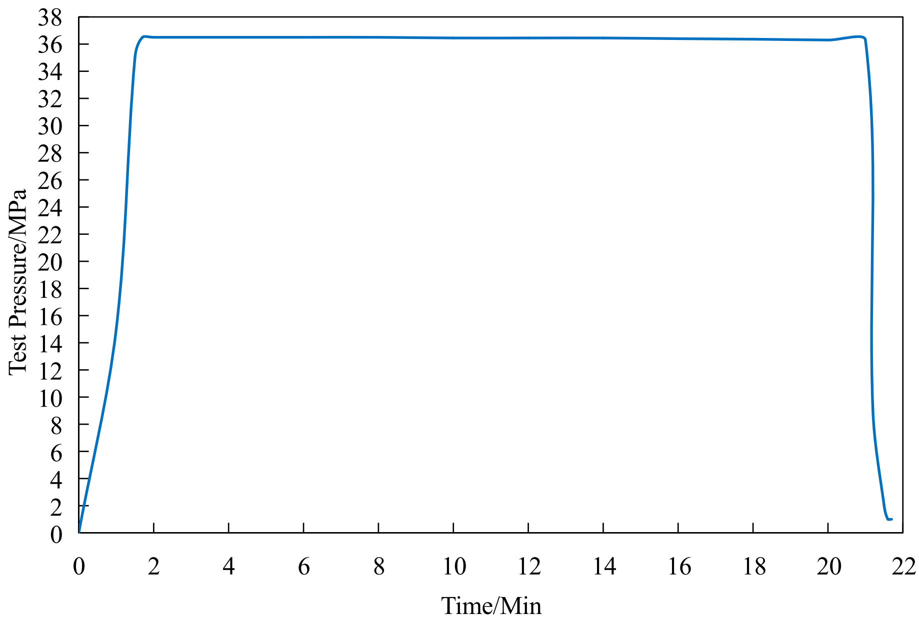

Figure 7 Pneumatic Seal Integrity Test Pressure-Time Profile for Tools

4.3. Drilling-Free Simulation at 35° Inclination and Circulation Port On-off Cycle Test

The staged cementing tool was mounted on a rotational fixture at a 35° inclination to simulate the well deviation effect of 35°.

As shown in Figure 8(a). The Opening plug is placed inside the tool. Upon pressure buildup, the shear pin is severed, allowing the Opening plug and the opening seat to eject smoothly and detach freely from the tool interior. Subsequently, the closing plug is inserted into the tool, and the pressure fitting is installed. When pressure rises to shear off the pin, the circulation port closes successfully. Continued pressurization then ejects both the closing seat and the closing plug.

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(a)Drop the opening plug (b)Open the circulation port (c)Drop the closing plug (d)Successfully detach

Figure 8 Drilling-Free Simulation at 35° Inclination and Circulation Port On-off Cycle Test

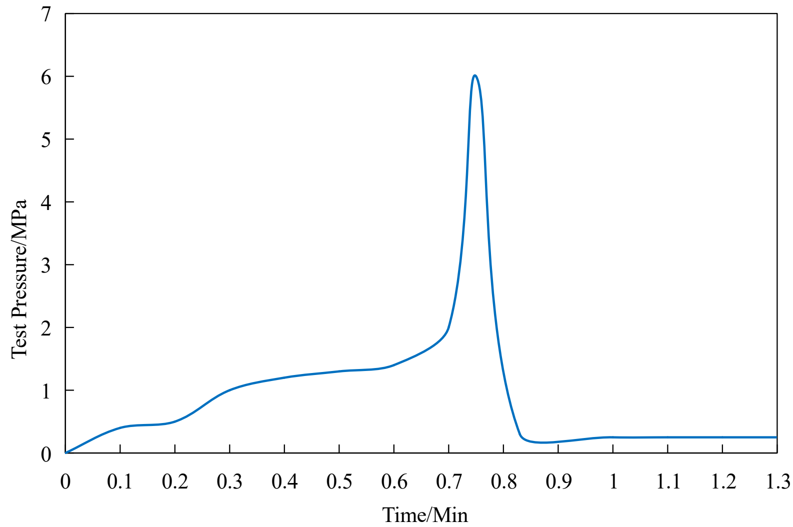

Figure 9 35°Pressure Curve of Inclination Simulation Opening Test

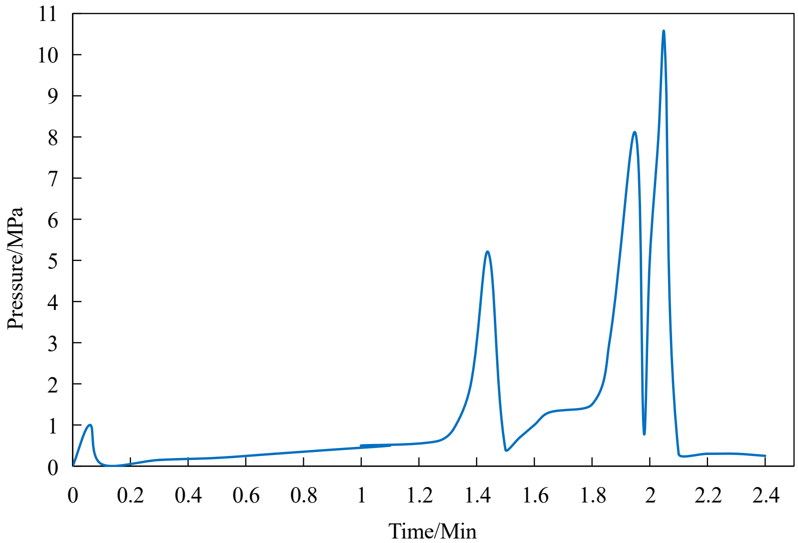

Figure 9 Pressure Curve of Simulated Plug Detachment Test at 35° Inclination

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4.4. Summary of Comprehensive Performance Testing for Drilling-Free Staged Cementing Tools

Based on current test feedback, the drilling-free staged cementing tools have successfully achieved gas and liquid sealing in both hydraulic and pneumatic sealing tests, with pressure drop results exceeding industry standards.

Under simulated 35° inclination conditions, the sequential actions including opening, closing, and detachment demonstrated reliable performance. This validates the drilling-free functionality, with shear pin pressures at each stage operating independently without interference, meeting downhole operational requirements. The tool is thus approved for progression to field trials. Test results and pressure data are detailed in Table 4.

Table 4 Conclusions of laboratory tests of tool

Test Item	Hydraulic Seal Integrity Test	Pneumatic Seal Integrity Test	Non-Drilling Port Opening Test at 35° Inclination	Non-Drilling Port Closing Test at 35° Inclination	Non-Drilling Plug Detachment Test at 35° Inclination
Test Pressure Data	110MPa	36MPa	6~8MPa	5~6MPa	8~11.5MPa
Test Conclusion	Pass	Pass	Pass	Pass	Pass

5. Field Test

5.1. Overview of Test Well

After completing the surface integrated performance test of the tool, the acid-resistant gas-tight drilling-free staged cementing tool was deployed for cementing operations in a directional well at Changqing Oilfield for field trials. The well has a total depth of 2,337 meters and a true vertical depth (TVD) of 2,316 meters. The cementing operation faced the following technical challenges:

(1)The cementing interval in this well spans 2,337 meters. Such extensive single-stage cementing generates high hydrostatic pressure within the static cement column, posing a significant risk of formation fracture during fluid placement.

(2)The target formation exhibits low fracture pressure resistance. During conventional cementing operations, the hydrostatic pressure exerted by the cement column exceeds the formation fracture pressure, resulting in circulation loss that prevents the cement slurry from returning to the surface in single-stage placement.

(3)The pay zone in this well exhibits extensive coverage spanning from 1,903.2m to 2,301.9m (total thickness: 398.7m). Single-stage cementing placement cannot effectively isolate the upper oil-water zones, leading to inadequate isolation with low-density slurries or even complete isolation failure.

In summary, severe circulation loss occurs during single-stage cementing operations in this area due to low formation fracture resistance, which fails to meet the requirements for single-stage placement. It is recommended to deploy staged cementing tools. For optimal placement depth of the staging tool, comprehensive consideration was given to cementing friction, hole diameter, well inclination, lithology, and the formation's equivalent circulation density (ECD).

Consequently, the stage collar for this well was set at 1413m (Zhiluo Formation), corresponding to a true vertical depth (TVD) of 1401m.

5.2. Staged Cementing Operations

According to field casing string design requirements, the drilling-free cementing tool employs long round threads for connections. The completion casing string assembly consists of: Float Shoe + Casing + Float Collar + Bump Ring + Casing + Staged Cementing Tool + Casing + Landing Joint.

Figure 9 Field Testing of Tools

For both primary and secondary cementing operations, a low-density lead slurry with a density of 1.35 g/cm^3 (1.35 SG) was utilized, followed by a tail slurry employing a fluid-loss control system at 1.90 g/cm^3 (1.90 SG).

Table 5 Tool field test pressure

Test Condition	Stage-1 Hydraulic Pressure/MPa	Port Opening Pressure/MPa	Port Closing Pressure/MPa	Sleeve Release Pressure/MPa	Stage-2 Hydraulic Pressure/MPa
Test Pressure Data	11-21	8	17	22	10-17-8-24

The field test pressures for primary bumping, secondary bumping, port opening, port closing, and plug detachment are detailed in Table 5. Notably, the field test pressures for port opening, closing, and plug detachment consistently exceeded those recorded in laboratory tests. This discrepancy arises because, during laboratory testing, the annular spaces inside and outside the staged cementing tool’s circulation ports were not pressurized. Pressure was applied solely above the plugs, driving them downward. In actual field operations, however, both annular spaces may contain pressurized fluids, generating counteracting forces during port actuation and plug detachment. Consequently, higher pressures are required to overcome these forces in field conditions.

The field trial successfully achieved port opening and closing operations of the staged cementing tool, verifying its operational reliability. No fluid loss occurred during cementing operations, demonstrating the tool's effectiveness in mitigating leakage risks during secondary cementing. Interpretation of cement bond log (CBL) and density logs confirmed 100% cementing compliance, indicating excellent bonding quality at the cement-formation interface.

6. Conclusions

(1) The tool employs a dual-sleeve design (closing sleeve and opening sleeve) integrated with locking blocks, combined with a specialized plug-triggered staging mechanism. This achieves circulation port switching and drilling-free detachment of attachments, resolving operational failures of conventional tools in deviated wells.

(2) For corrosive service conditions, material selection based on ECE software recommendations resulted in the adoption of corrosion-resistant alloys ≥13Cr. This ensures an average corrosion rate <0.025 mm/year in acidic environments at 90°C.

(3) Laboratory tests confirm that the tool exceeds industry standard SY/T 5150-2013 in: hydraulic sealing (110 MPa/30 min, pressure drop ≤0.2 MPa), pneumatic sealing (36.5 MPa/30 min, pressure drop ≤0.2 MPa), and drilling-free performance at 35° inclination.

(4) Field applications demonstrate the tool’s effectiveness in reducing leakage risks in long cementing intervals, achieving 100% cementing qualification rate. It provides critical technical support for wellbore integrity in highly acidic environments.

Acknowledgements

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References

[1] QIN Jinli,LI Weiguo ,ZENG Yanjun, et al. Application of Paker Stage Cementing Tool in Puguang Gas Field [J].Driling and Production Technology,2023,46(6):165-169.

[2] ZHENG Dujian, CHEN Yuhao, ZOU Chuanyuan, et al. New Technology of Stage Cementing and Its Application in Permian in Tarim Basin[J].Drilling and Production Technology, 2023, 46(5): 29–34.

[3] WU Yanhua, ZHAN Ning, XUE Weiqiang. Cementing Technology of φ244.5 mm Technical Casing and High-Density Cement Slurry in Well Mingbulak 15[J]. Oil Drilling & Production Technology, 2020, 42(6): 720–725.

[4] SU Yi’nao, LU Baoping, LIU Yansheng, ZHOU Yingcao, LIU Xiushan, LIU Wei, ZANG Yanbin. Status and research suggestions on the drilling and completion technologies for onshore deep and ultra deep wells in China[J]. Oil Drilling & Production Technology, 2020, 42(5): 527–542.

[5] WU Zhiqiang, WU Guang, XING Xuesong. Sealing Integrity of Cement Sheath Under the Condition of CO_2 Corrosion-Stress Coupling[J]. Drilling Fluid & Completion Fluid, 2024, 41(2): 220–230.

[6] ZHANG Kun, SUN Yue, WANG Chijia, et al. Research on CO_2 Corrosion and Protection in Carbon Capture, Utilization and Storage[J]. Surface Technology, 2022, 51(9): 43–52.

[7] LI Bin, WANG Da, YANG Chunlei. Structural optimization design of self-adapted sealing ring for flat gate valve of christmas tree[J]. Lubrication Engineering, 2019, 44(11): 105–111.

[8] TANG Sui, SONG Shaohua, CHEN Sen, et al.CO_2 Corrosion Resistance Evaluation of Packer Rubber in CCUS Wells[J]. Xinjiang Oil & Gas, 2024, 20(4): 50–59.

[9] WANG Xiaohong, WANG Hailun, LIN Yuanhua. Corrosion resistance of the rubber in gas and liquid phase environment containing high carbon dioxide[J]. APPLIED CHEMICAL INDUSTRY, 2019, 48(S2): 169-173.

[10] Pu Lantian. Study on Two-stage Cementing Technology[D]. Chongqing University of Science and Technology.

[11] SUN Gang, WU Shenhuai, XIONG Gang, SHEN Xiaoyan. Corrosion Analysis and Protection Measures for MCRC Sulfur Recovery Unit in Northwestern Sichuan[J]. Chemical Engineering of Oil & Gas, 2009, 38(01):46-50+95-96.

[12] ZHAO Kaifeng, CHEN Zuoming, XU Jianguo, SUN Xiaoguang et al. Corrosion Cause Analysis of Oil Well Casing and Effect Evaluation of Corrosion Protection Measures[J]. Corrosion & Protection, 2023, 44(11): 86-92.